Shale gas production: potential versus actual greenhouse gas emissions*

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Shale gas production: potential versus actual greenhouse gas emissions

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Abstract
Estimates of greenhouse gas (GHG) emissions from shale gas production and use are controversial. Here we assess the level of GHG emissions from shale gas well hydraulic fracturing operations in the United States during 2010. Data from each of the approximately 4000 horizontal shale gas wells brought online that year are used to show that about 900 Gg CH_4 of potential fugitive emissions were generated by these operations, or 228 Mg CH_4 per well—a figure inappropriately used in analyses of the GHG impact of shale gas. In fact, along with simply venting gas produced during the completion of shale gas wells, two additional techniques are widely used to handle these potential emissions: gas flaring and reduced emission 'green' completions. The use of flaring and reduced emission completions reduce the levels of actual fugitive emissions from shale well completion operations to about 216 Gg CH_4, or 50 Mg CH_4 per well, a release substantially lower than several widely quoted estimates. Although fugitive emissions from the overall natural gas sector are a proper concern, it is incorrect to suggest that shale gas-related hydraulic fracturing has substantially altered the overall GHG intensity of natural gas production.

Keywords: shale gas, hydraulic fracturing, GHG emissions, fugitive emissions, reduced emission completions

S Online supplementary data available from stacks.iop.org/ERL/7/044030/mmedia

1. Introduction

Over the past decade, economically recoverable shale gas has transformed the US natural gas industry, with some analysts characterizing it as a 'revolution' (Deutch 2011, Jacoby *et al* 2012). With shale driven growth, the US has become the world's largest gas producer (IEA 2011). The low gas prices that have accompanied this production boom have led to a renewed growth in gas demand by industrial users, a recovery viewed as extremely unlikely just a decade ago. The rise of shale gas has not been without controversy, however, with important concerns raised regarding water pollution (Osborn *et al* 2011), greenhouse gas (GHG) emissions, particularly those related to hydraulic fracturing (Howarth *et al* 2011a, 2011b, 2012), and uncertainty in estimates of the resource scale (Jacoby *et al* 2012, Urbina 2011, MIT 2011, Lee and Sidle 2010). In this analysis we focus on the issue of fugitive GHG emissions associated with shale gas fracturing and provide estimates of potential and actual emissions.

2. Hydraulic fracturing and GHG emissions

The economic production of shale gas is only possible through the use of hydraulic fracturing to increase production rates

from the extremely low-permeability shale formations. The hydraulic fracturing process has two main stages: injection and flowback. During injection, a slurry made up of a carrier fluid, typically water, and a proppant agent, typically sand, is forced into the well at pressures significant enough to induce fractures in the reservoir rock. These propped fractures allow gas in the formation to flow from the well at economically acceptable rates. After the injection phase is completed, flowback takes place. Here some of the initially injected fluid returns to the surface over the course of a week or more. During flowback, the well also begins to produce gas. It is the amount of this gas, and how it is handled, that has been central to the debate about the GHG intensity of shale development. In 2011, the EPA revised upwards its GHG inventories for the natural gas system (EPA 2011), and some have attributed this increase to the expanded production of shale gas and the associated increase in hydraulic fracturing. It has been argued that large amounts of gas are directly vented to the atmosphere during flowback, and that this means shale gas has a significantly higher GHG intensity than conventional gas production (Howarth *et al* 2011a, 2011b). In fact, with some specific assumptions about the global warming potential of gas it has been suggested that the GHG impact of shale gas might be greater than that of coal on a lifetime basis (Howarth *et al* 2011a, 2011b). This perspective has been widely articulated via popular media (e.g., Soraghan 2011, McDonald 2011).

Debate regarding this issue has been added to by research published by NOAA scientists (Petron *et al* 2012) that studied methane and other fugitive GHG levels in air samples taken in Colorado's Denver–Julesburg oil and gas basin. Their results suggest that fugitive emissions in Colorado's Weld County during 2008 amounted to 3.8% of the county's total gas production that year. The study area, the Denver–Julesburg Basin is a tight sandstone formation that produces appreciable amounts of both gas and oil. In 2008, the year of the study, there were 850 tight gas wells and 1583 oil/condensate wells drilled in the Denver–Julesburg area (HPDI 2012). An important point regarding the study is that it assessed fugitive emissions levels from the entire gas and oil production system in the basin, which includes many complex upstream and midstream systems widely known as fugitive emissions sources including gathering pipelines, compressor station and condensate tanks (EPA 2012a, 2011). Nevertheless, some have interpreted the NOAA analysis as a quantification of fugitive emissions resulting from hydraulic fracturing alone (Tollefson 2012).

The conclusions of Howarth *et al* (2011b), have been questioned by some analysts (DOE 2011, Cathles *et al* 2012), and several groups working on the topic have come to different conclusions regarding the relative GHG impact of shale gas. Burnham *et al* (2011) concludes that the life-cycle GHG emissions from shale gas are slightly less than that of conventional gas, Weber and Clavin (2012) suggest they are approximately equal, while Jiang *et al* (2011) and Stephenson *et al* (2011) both conclude that shale gas has a lifetime GHG impact that is slightly higher than that of conventional gas. All of these groups do however conclude that the GHG impact

of electricity generated using shale gas is significantly less than that of generated with coal. Howarth *et al* stand by their conclusions (Howarth *et al* 2012), pointing out the significant upward revision in EPA estimates of fugitive emissions from unconventional wells in the EPA's 2011 inventory (EPA 2011). Their conclusions are also supported, at least in the case of Barnett shale wells, by the analysis in Hultman *et al* (2011).

3. Analysis

Analysis of this controversy begins with quantification of potential emissions produced during well flowback. This requires knowledge of the duration of the flowback stage, and the rate of gas production during that period. The EPA assumes that the flowback period lasts from 3 to 10 days (EPA 2011). A recent industry-sponsored survey suggests 3 to 8 days (ANGA 2012). The analysis of Howarth *et al* (2011a) assumes 9 days for the wells in the Barnett shale and 10 days in the Haynesville shale. Here we use a 9 day flowback period for wells in each of the major shale plays. Although it is certain that flowback durations vary from well to well, our 9-day assumption is at the conservative end of the reported range. Measured data on the rate of flowback from Haynesville shale wells reported by Fan *et al* (2010) show that within 9–10 days, the level of fluid production falls by ~75%, and this confirms that 9 days is a reasonable estimate. We assume that gas production during flowback from a given well can be modeled as ramping linearly from zero at flowback initiation to the peak recorded production rate for that well at flowback completion. This assumption is supported by data presented during a recent EPA workshop (EPA 2012b), and by both simulation results and recorded gas production rates during the flowback of shale wells reported by Fan *et al* (2010). Integrating this production profile over the 9 day flowback period yields the potential fugitive emissions estimate for each well.

In this report we assess the level of fugitive GHG emissions resulting from the hydraulic fracturing of 3948 horizontally drilled shale gas wells brought online in the US during 2010 (HPDI 2012), assuming a number of gas handling scenarios, which involve different levels of venting, flaring and gas capture. Table 1 shows the potential emissions estimates assuming the mean well peak production rates in each shale play for 2010. The table also illustrates the substantial well-to-well variability in potential emission levels by showing the estimates for the 20th, 50th and 80th percentile peak production rates. The peak production rate data underlying the values reported in table 1 can be seen in table S1 of the supplementary materials (available at stacks.iop.org/ERL/7/044030/mmedia). The variation in initial well productivity within and between the shale plays is driven in large part by underlying geological, geo-mechanical, geochemical and petrophysical characteristics of the shale formations. Reservoir pressure, total organic content, thermal maturity, porosity and other factors can all differ within and between plays, and this in turn results in well-to-well variation in productivity (Jarvine *et al* 2007, Curtis *et al* 2012, Hammes *et al* 2011, Baihly *et al* 2010). Aggregating the data in table 1

Table 1. Per-well hydraulic fracturing-related potential fugitive emissions from 2010 vintage US horizontal shale gas wells. (Source: authors' calculations based on HPDI 2012.)

Per-well potential emissions: (1×10^3 m^3 natural gas)	Barnett	Fayetteville	Haynesville	Marcellus	Woodford
Mean:	273	296	1177	405	487
P80:	385	409	1538	573	685
P50:	234	285	1108	342	413
P20:	138	167	754	195	230

Table 2. Total hydraulic fracturing-related potential fugitive emissions from US shale gas wells brought online in 2010. (Source: authors' calculations based on HPDI 2012.)

	Barnett	Fayetteville	Haynesville	Marcellus	Woodford	All plays
Mean per-well potential fugitive emissions: (1×10^3 m^3 of natural gas)	273	296	1177	405	487	—
No. of horizontal wells	1785	870	509	576	208	3948
Total potential fugitive emissions: (1×10^6 m^3 of natural gas)	487	257	599	234	101	1678
Total potential fugitive methane emissions: (Gg CH$_4$)	262	138	322	125	54	902

Table 3. Shale gas hydraulic fracturing-related potential fugitive emissions as a percentage of estimated ultimate recovery assuming mean well production performance rates and 30 yr and 15 yr producing lifetimes. (Source: authors' calculations based on HPDI 2012.)

	Barnett (%)	Fayetteville (%)	Haynesville (%)	Marcellus (%)	Woodford (%)
30 yr lifetime	0.39	0.39	0.78	0.39	0.39
15 yr lifetime	0.54	0.52	0.99	0.53	0.52

for the total number of wells brought online in 2010 yields an overall estimate of hydraulic fracturing-related potential fugitive emissions from the five plays of 902 Gg CH$_4$. The details of this aggregation are shown in table 2. For comparison, the EPA GHG inventory for the upstream gas sector estimates total 2010 fugitive emissions of 6002 Gg CH$_4$.

It is useful to compare the per-well potential emissions from table 1 to the estimated ultimate production from wells in each play. There is appreciable uncertainty regarding the level of ultimate recovery that can be expected from shale wells. Much of this is due to the limited production history of the shale resource and, as yet, not well understood mechanisms of production in ultra-low permeability reservoirs (Anderson *et al* 2010, Lee and Sidle 2010). To account for this uncertainty we assume two well production lifetimes in this analysis; the commonly assumed 30 yr lifetime, and a more conservative 15 yr lifetime. It is important to acknowledge though that there is legitimate debate ongoing regarding whether the productive lifetimes of these wells may in fact be appreciably shorter than even our 15 yr case (Berman 2012, Hughes 2011). The results of the comparison between potential emissions produced during flowback and estimates of ultimate recovery based on 30 and 15 yr producing lifetimes are shown in table 3. The results indicate that in most shale plays, hydraulic fracturing-related potential fugitive emissions represent 0.4–0.6% of a well's estimated ultimate

recovery. In the Haynesville, the ratio is higher at 0.8–1%, owing to the high initial production and production decline rates in that play, which are due to that particular shale's highly over-pressured reservoir (Baihly *et al* 2010). Should it become clear that shorter lifetimes are more representative, then the ratio of potential emissions to ultimate recovery will increase, though not proportionally as shale wells tend to be most productive during their early lives. Details of actual production dynamics from the ensemble of shale wells drilled since 2005 can be found in section S2 of the supplementary materials (available at stacks.iop.org/ERL/7/044030/mmedia).

The proportions of the potential fugitive emissions that are vented, flared, or captured and sold via a reduced emission 'green' completion determine the actual GHG intensity of shale gas-related hydraulic fracturing. In this analysis we use specific GHG intensities for venting, flaring and reduced emission completions of 13.438 kg CO$_2$e, 1.714 kg CO$_2$e and 1.344 kg CO$_2$e respectively, based upon a 100 yr Global Warming Potential (GWP) for CH$_4$. Shindell *et al* (2009) argue that the use of a 100 yr integration period underestimates the actual warming impact of CH$_4$ and suggests that a higher GWP factor, based on a 20 yr integration period be used instead. Because the various GHGs have different lives in the atmosphere (e.g., on the scale of decade for CH$_4$ but centuries for CO$_2$ and thousands of years for some other GHG gases), the IPCC (2007) provides this

Table 4. Per-well actual fugitive GHG emissions from shale gas-related hydraulic fracturing in 2010. (Source: authors' calculations based on HPDI 2012).

	Barnett	Fayetteville	Haynesville	Marcellus	Woodford
Per-well GHG emissions: Mg CH_4/well (related CO_2 emissions are added based on 100 yr CH_4 GWP)					
All vented	146.7	159.1	632.7	217.7	261.8
Current field practice	35.1	38.0	151.3	52.1	62.6

factor for 20-, 100-, and 500 yr integration periods and uses 100 yr GWPs. MIT (2011) argues that 20 yr GWP would emphasize the near-term impact of methane but ignore serious longer-term risks of climate change from GHGs that will remain in the atmosphere for hundreds to thousands years.

For a comparison, the specific GHG intensities of venting, flaring and reduced emissions completions assuming a 20 yr GWP for CH_4 are detailed in section S3 of the supplementary materials (available at stacks.iop.org/ERL/7/044030/mmedia).

Significant opaqueness surrounds real world gas handling practices in the field, and what proportion of gas produced during well completions is subject to which handling techniques. Diverse opinions on this question exist even within the gas industry. Some analysts state that gas companies have had a policy of not investing in gas conservation measures due to the low rate of return (one referee of this paper pointed out an oral presentation given at the 2012 Goldschmidt International Geochemistry Conference in Montreal where gas insiders stressed this point and argued that venting of methane is a common practice since flaring draws public attention). By contrast, an industry survey of unconventional gas producers has suggested that reduced emission completions are being used on more than 90% of shale wells completions, and that in the case of those wells not subject to a reduced emissions completion, the duration of flowback is rarely more than 3 days (ANGA 2012). Some of the contemporary analysis on shale gas-related fugitive emissions has not attempted to account for the impact of real world gas handling field practice. For example, in Howarth et al (2011b) it is assumed that all potential fugitive emissions are vented. This is an unreasonable assumption, not least because some producing states have regulation requiring flaring as a minimum gas handling measure. The EPA in its quantification of fugitive emissions does assume a certain proportion of gas is flared (EPA 2011, 2012a); however, it does not separate fugitive emissions from shale wells with those from tight and other unconventional gas sources. Furthermore, the EPA analysis does not adequately assess gas capture levels, particularly in regions where flaring is required.

We assess several gas handling scenarios, ranging from the assumption that all potential emissions are vented (Howarth et al 2011b), to that suggested by a gas industry group in which 93% of potential fugitive emissions are captured (ANGA 2012). However, our main estimate of actual fugitive emissions is based on a 'current field practice' gas handling scenario, where 70% of potential fugitives are captured, 15% vented, and 15% flared. This we believe is a reasonable representation of current gas handling practices in the major shale plays (EPA 2012b). (Further discussions of gas handling scenarios are presented in section S3 of the supplementary materials available at stacks.iop.org/ERL/7/044030/mmedia.) Table 4 contrasts the level of per-well actual fugitive emissions based upon the assumption of the 'current field practice' scenario and the 'all vented' scenario. Compared to the all-vented analysis (Howarth et al 2011b), which reports emissions from Barnett as 252 Mg CH_4/well (or 370 000 m^3 CH_4) and 4638 Mg CH_4/well (6 800 000 m^3 CH_4) for Haynesville, our mean estimates are 35.1 Mg CH_4/well and 151.3 Mg CH_4/well, respectively.

Beyond regulation, the methods selected to handle gas during well completions in the field are driven by economics. In the case of conventional gas wells, the volumes of potential emissions produced during completion are very low. According to the EPA, on average, 1040 m^3 CH_4 (36.36 Mcf) are produced by a conventional well completion (EPA 2010). The economic value of this gas would certainly not justify the use of a reduced emission 'green' completion. By contrast, the level of potential emissions from shale wells is very large. In Howarth et al (2011b) it is stated that 3.2% of the estimated ultimate recovery from a Haynesville shale well is produced during flowback. In that case, 3.2% of estimated ultimate recovery amounts to 6 800 000 m^3 CH_4. This is a very considerable amount of gas and assuming a conservative long-run wellhead gas price of \$4.00/MMBtu (MIT 2011, NYMEX 2012, EIA 2012), simply venting, or indeed flaring this gas would amount to a revenue loss of \$1.2 million for the operators. Admittedly, this is an extreme example since the performance of the particular Haynesville well in question is not representative of a typical Haynesville well; however, even when considering mean shale well performance data, the value of gas produced during flowback is substantial, and likely to warrant the cost of capture. Based on our mean estimates of potential emissions shown in table 1, the gross values of capturing this gas using a reduced emission completion ranges from \$39 000 for a Barnett well to \$166 000 for a Haynesville well. The aggregate gross value of the gas produced during flowback from the 3948 shale wells considered in this study amounts to \$320 million. Capturing potential emissions is not without cost, of course, but these costs appear to be relatively modest (a detailed discussion of the variability in the gross value of gas produced during flowback, and the costs associated with reduced emission completions can be found in section S4 of the supplementary materials available at stacks.iop.org/ERL/7/044030/mmedia). If the cost of reduced emission completion is \$1000 per day as stated by Devon (2008), 95% of the 2010 Barnett wells

yielded positive net revenues, i.e., operators added to the value of their wells by capturing the potential fugitive emissions. Even at twice this reported capture cost, $2000 per day, 83% of the 2010 Barnett wells would still positive net revenues, and this trend is repeated in the all the other shale plays. The results of a sensitivity analysis exploring the impact of reduced emissions completion costs and gas price variation on the 2010 Barnett shale well ensemble are shown in figures S5 and S6 of the supplementary materials (available at stacks. iop.org/ERL/7/044030/mmedia).

4. Conclusions

Taking actual field practice into account, we estimate that in 2010 the total fugitive GHG emissions from US shale gas-related hydraulic fracturing amounted to 216 Gg CH_4. This represents 3.6% of the estimated 6002 Gg CH_4 of fugitive emissions from all natural gas production-related sources in that year (EPA 2012a, 2012b). The entire natural gas value chain is estimated to have produced 10 259 Gg CH_4 of fugitive emissions in 2010, or about 3.1% of the nation's total GHG inventory (EPA 2012a, 2012b). Thus under a goal of GHG reduction it is clear that increased efforts must be made to reduce fugitive losses from this system. However, it is also clear is that the production of shale gas and specifically, the associated hydraulic fracturing operations have not materially altered the total GHG emissions from the natural gas sector. Furthermore, for the vast majority of contemporary shale gas wells, the revenues gained from using reduced emissions completions to capture the gas produced during a typical flowback cover the cost of executing such completions.

Acknowledgments

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